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Polariton local states in periodic Bragg multiple quantum well structures

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Abstract. Defect polariton states in Bragg multiple-quantum-well structures are studied along with defect induced changes in transmission and reflection spectra. Analytical results for eigen frequencies of the local states and for respective transmission coefficients are obtained. It is shown that the local polaritons result in resonance tunneling of light through the stop band of MQW structure, but unlike other types of local states, the transmission resonance frequencies are always shifted with respect to eigen frequencies of the local modes. Exciton homogeneous broadening is taken into account phenomenologically and recommendations regarding the experimental observation of the predicted effects are given.

Introduction

Optical properties of multiple quantum wells (MQW) have attracted a great deal of interest recently [1–8]. The exciton–photon coupling results in MQW polaritons — coherently coupled quazi-stationary excitations of quantum well (QW) excitons and transverse electromagnetic field. So called Bragg structures, in which interwell spacing, a, is tuned to the exciton resonance frequency Ω_0 ($a = \lambda_0/2$, where λ_0 is the wavelength of the light at the exciton frequency Ω_0) attracted special attention [2, 5, 7, 8]. A well-pronounced polariton gap was observed in recent experiments [8] with GaInAs/GaAs Bragg structures with the number of wells up to 100. These experiments convincingly demonstrated that despite homogeneous and inhomogeneous broadening the coherent exciton–photon coupling in long MQW is experimentally feasible. Polariton effects arising as a result of this coupling open up new opportunities for manipulating optical properties of quantum heterostructures.

One of such opportunities is associated with introducing defects in MQW structures. These defects can be either QW's of different compositions replacing one or several "host" wells, or locally altered spacing between elements of the structure. This idea was first applied to MQW by Citrin [9], where it was shown that different defects can give rise to local exciton–polariton modes in infinite MQW. Unlike regular interface modes in superlattices, local modes in a defect MQW structure exists at $k_{\|} = 0$ and can be excited at normal incidence. In this paper we present results of detailed studies of local polariton modes (LPM's) produced by two different types of individual defects in Bragg MQW structures. We consider LPM's with zero in-plane wave vector only. Such modes are excited by light incident in the growth direction of the structure, and can result in resonance transmission of light through the polariton gap of the host structure. Using parameters of a realistic InGaAs/GaAs system studied experimentally in Ref. [8], we give recommendation on the experimental observation of the LPM's.

1. Eigen frequencies of local polaritons in defect MQW's

We describe optical properties of MQW's using polarization density of the form: $\mathbf{P}(\mathbf{r}, z) = \mathbf{P}_n(\mathbf{r})\delta(z - z_n)$, where $\mathbf{r}$ is an in-plane position vector, z_n represents a coordinate of the

n-th well, and $\mathbf{P}_n$ is a surface polarization density of the respective well. The latter is determined by the exciton dynamics, described in the considered situation by the equation $\left(\Omega_n^2 - \omega^2\right) P_n = \frac{1}{\pi} c \Gamma_n E(z_n)$, where Ω_n and Γ_n are exciton frequency and exciton-light coupling of the n-th QW, respectively. In an infinite pure system, all $\Gamma_n = \Gamma_0,\ \Omega_n = \Omega_0,\ z_n = na$, where $a = \lambda_0/2$ is the Bragg's interwell separation.

The spectrum of ideal periodic MQW's has been studied in many papers [1, 3, 10, 11, 12]. In the specific case of Bragg structures, the exciton resonance frequency, Ω_0, is at the center of the bandgap determined by the inequality $\omega_l < \omega < \omega_u$, where $\omega_l = \Omega_0 \left(1 - \sqrt{2\Gamma_0/\pi\Omega_0}\right)$ and $\omega_u = \Omega_0 \left(1 + \sqrt{2\Gamma_0/\pi\Omega_0}\right)$ [10]. This bandgap is the frequency region where we will look for new local states associated with the defects. Two types of defect are of the greatest interest. One is associated with replacing an original QW with a QW with different exciton frequency (Ω-defect), and the other one results from perturbation of an interwell spacing between two wells. The dispersion equation for Ω-defect has, in the case of the Bragg structures, two solutions, one below Ω_0 and one above. One solution demonstrates a radiative shift from the defect frequency Ω_1,

$$\omega_{\text{def}}^{(1)} = \Omega_1 - \Gamma_0 \frac{\Omega_1 - \Omega_0}{\sqrt{(\omega_u - \Omega_1)(\Omega_1 - \omega_l)}}, \tag{1}$$

while the second solution splits off the upper or lower boundary depending upon the sign of $\Omega_1 - \Omega_0$:

$$\omega_{\text{def}}^{(2)} = \omega_{u,l} \pm \frac{1}{2}(\omega_u - \omega_l) \left(\frac{\pi}{2} \frac{\Omega_1 - \Omega_0}{\Omega_0}\right)^2, \tag{2}$$

where one chooses ω_u and "$-$" for $\Omega_1 > \Omega_0$, and ω_l and "$+$" in the opposite case. It can be seen that the shift of $\omega_{\text{def}}^{(1)}$ from the defect exciton frequency Ω_1 is negative for $\Omega_1 > \Omega_0$ and positive for $\Omega_1 < \Omega_0$.

The a-defect is actually a cavity, whith QW's playing the role of the mirrors. Unlike regular cavities, however, the "mirrors" in our case are themselves optically active, and this fact is responsible for significant peculiarities of the case under consideration. Eigen frequencies for this situation can be found using transfer matrix approach. Solutions of the respective dispersion equation can be approximated as

$$\omega_{\text{def}}^{(1)} = \Omega_0 - \frac{\omega_u - \omega_l}{2} \frac{(-1)^{\left[\frac{\xi+1}{2}\right]} \sin(\pi\xi/2)}{1 + \dfrac{\omega_u - \omega_l}{2\Omega_0} \xi (-1)^{\left[\frac{\xi+1}{2}\right]} \cos(\pi\xi/2)}, \tag{3}$$

$$\omega_{\text{def}}^{(2)} = \Omega_0 + \frac{\omega_u - \omega_l}{2} \frac{(-1)^{\left[\frac{\xi+1}{2}\right]} \cos(\pi\xi/2)}{1 - \dfrac{\omega_u - \omega_l}{2\Omega_0} \xi (-1)^{\left[\frac{\xi+1}{2}\right]} \sin(\pi\xi/2)}, \tag{4}$$

where $\xi = b/a$, and [...] denotes an integer part. Therefore, for $\Gamma_0 \ll \Omega_0$ and not very large ξ, $\xi \ll \Omega_0/\Gamma_0 \simeq 10^4$, both solutions are almost periodic functions of b/a with the period of 1. These solutions oscillate between respective boundaries of the gap (ω_u or ω_l) and the exciton frequency Ω_0.

2. Defect local polariton modes and transmittance and reflectance experiments

Resonance transmission in the case of Ω-defect is described by

$$T = \frac{4\gamma_\Omega^2}{Q^2}\frac{(\omega - \omega_T + Q)^2}{(\omega - \omega_T)^2 + 4\gamma^2}, \tag{5}$$

where $Q = \omega_T - \Omega_1$, and parameter γ_Ω is given by

$$\gamma_\Omega = \pi\Omega_0\left(\frac{\omega_{def} - \Omega_0}{\Omega_0}\right)^2 e^{-\kappa N a}. \tag{6}$$

The transmission spectrum Eq. (5) has a shape known as Fano resonance where ω_T is the resonance frequency, at which transmission turns unity, parameters γ_Ω and Q describe the width and the assymetry of the resonance respectively. The resonance transmission in the case of a-defect is described by the standard Breit–Wigner shape with the half-width, γ_a, proprtional to $\sqrt{\Gamma_0\Omega_0}e^{-\kappa N a}$.

In general, the transmission resonance frequency in both cases is shifted with respect to the frequency of the local mode. The shift, though exponentially small for long systems considered here, is of the same order of magnitude as the width of the resonance, and is, therefore, significant.

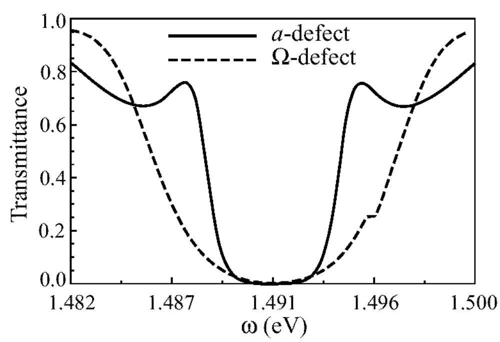

Fig. 1. Numerically generated transmission spectra of GaInAs/GaAs MQW's with Ω- (dashed line) and a—(solid line) defects. Input parameters were chosen from Ref. [ ]: $\Omega_0 = 1.491$ eV, $\Gamma_0 = 27\,\mu$eV, and exciton relaxation parameter $\gamma_{hom} = 0.28$ meV. The length of the system is $N = 200$.

Reaction of the transmission resonance to the presence of a homogeneous broadening in the case of Ω-defect is determined by interplay between the width of the resonance and the assymetry parameter Q. The later is rather small, and, therefore, in practically important cases, is responsible for the survival of the resonance. For InGaAs/GaAs MQW's of Ref. [ ] homogeneous broadening is rather large, and instead of a full fledged Fano resonance one will observe in such systems only a small spike (see Fig. 1). It does not preclude, however, an opportunity to observe such a resonance in other systems with an increased exciton-photon coupling. For a-defect the situation is completely different (Fig. 1). The large prefactor in the resonance width parameter γ makes this defect quite stable with respect to absorption. The resonance transmission with two nice maximums can, therefore, be observed in the systems with lengths ranging between 100 and 400 wells in the case of InGaAs/GaAs systems.

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